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Propulsion Report 183

THE DETECTION OF SEEDED FAULTS IN AN EPICYCLIC GEARBOX BY SIGNAL AVERAGING OF THE VIBRATION

by

P.D. McFadden

and

I.M. Howard

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THE DETECTION OF SEEDED FAULTS IN AN EPICYCLIC GEARBOX BY SIGNAL AVERAGING OF THE VIBRATION

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SUMMARY

This paper reports on a new technique for obtaining signal averages of the individual planetary gears and the sun gear using a single transducer. Individual epicyclic components can now be analysed using standard signal average enhancement techniques to diagnose gear condition. Analyses of data from epicyclic gearboxes with seeded faults are presented.

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1. INTRODUCTION

Signal averaging is a powerful digital signal processing technique which enables the extraction of periodic waveforms from additive noise by sampling and ensemble averaging the noisy signal under the control of a second noise-free signal which is synchronous with the required signal. An important practical application of signal averaging lies in the condition monitoring of rotating machinery, as it enables the vibration produced by the meshing of the teeth of the individual gears to be separated from the total vibration of a complex gearbox. The signal average of the vibration of a gear shows the vibration of that gear in the time domain over one complete revolution, so that the pattern of vibration produced by the meshing of the teeth become visible. Any variations in the vibration between the teeth become apparent, so that local damage such as a fatigue crack in a gear tooth may be detected by simple examination of the signal average. For even earlier warning of damage, there is now a variety of digital signal processing techniques which can be applied to the signal average to highlight the variations in the vibration between the teeth [1-3]. These techniques, commonly referred to as enhancement techniques, remove the pattern of vibration which corresponds to the average tooth meshing vibration, so that the variations in the remaining signal are made more conspicuous.

In the majority of gear systems, the gears rotate on shafts and bearings which are mounted in fixed positions in the gearbox case. The procedure for calculating the signal average of the vibration of these gears is now well established, and signal averaging has already made useful contributions to the monitoring of such gears. The problem area until now has been epicyclic gears, which feature a set of identical planet gears mounted in a frame or carrier which rotates around a central sun gear, all fitted within an internal gear called the annulus. The sharing of the load by the planet gears enables high torques to be transmitted, so that epicyclic gears are favoured in large marine and industrial gearboxes and in the last stage in the main rotor gearbox of almost all helicopters. Unfortunately the relative motion of the planet gears, the sun gear and the annulus gear, together with the multiplicity of the contact regions, makes the signal averaging of epicyclic gears difficult. If a vibration transducer such as an accelerometer is mounted on the gearbox casing, then the planets move relative to the transducer. Meshing occurs between each planet gear and the annulus gear, and between the planet gears and the sun gear. A typical helicopter gearbox may feature five planet gears, giving ten regions of contact, all producing vibration at the same tooth meshing frequency. By synchronizing with the rotation frequencies of the planet gears or sun gear, signal averages can be produced which are a composite of the vibration of all of the planet gears [4]. However with five planet gears, for example, the change in the signal average resulting from damage to any one planet gear will be averaged to only one-fifth of its magnitude, so that the damage must be far more severe before it can be detected. Clearly, there is a need for signal averages of the individual planet gears and sun gear, so that damage to one gear may be identified as soon as possible by the application of the existing enhancement techniques for fixed gears.

This paper outlines the principles of a new technique which has been developed for calculating the signal averages of the individual planet gears and the sun gear. The technique is demonstrated by calculating the signal averages

for the planet gears and sun gear in a small industrial epicyclic speed reducer and detecting seeded faults within the gearbox.

2. THEORETICAL DEVELOPMENT

Consider the simple epicyclic gear system illustrated in Figure 1(a). The numbers of teeth on the annulus, planet and sun gears respectively are Na, Np and Ns. The annulus gear is fixed to the gearbox case and a vibration transducer is fixed to the rim of the annulus gear. The rotation frequencies of the planet and sun gears and the planet carrier are fp, fs and fc respectively. The rotation frequency of the planet gears and sun gear relative to the planet carrier may be found by superimposing a whole body counter-rotation of fc to bring the carrier to rest, as illustrated in Figure 1(b). It can be seen that the rotation frequencies of the planet gears and sun gear relative to the carrier are fp+fc and fs-fc respectively.

By synchronizing the sampling of the vibration signal with the rotation frequency of the carrier fc, the signal average for the annulus gear can be calculated. It is found that the signal average for the annulus gear, representing one complete revolution of the planet carrier, shows a peak in the level of the tooth meshing vibration as each planet gear passes the transducer. Clearly, the transmission path between the gear teeth which are in mesh and the transducer has an important effect on the measured vibration level. It would be expected that the largest amplitude will be measured when a planet gear is closest to the transducer, and that when that planet gear is on the far side of the annulus gear then its contribution to the measured vibration will be negligible in comparison. As the planet carrier rotates, the vibration due to a single planet gear, as measured by the transducer, is modulated at the carrier rotation frequency. This phenomenon has already been used to explain the asymmetry of the modulation sidebands seen in the amplitude spectrum of the vibration of epicyclic gears [5]. It now provides the key to a simple new technique for separating the vibration of the individual planet gears and the sun gear.

If the signal from the vibration transducer is sampled during a short time interval when a planet gear is closest to the transducer, then the values obtained will be dominated by the vibration produced by the meshing of that particular planet gear with the annulus gear. Over a width of the window, the transfer function between the region of tooth contact and the transducer may be considered constant. The window of sampled data is then stored in an accumulator, as illustrated in Figure 2. One revolution of the carrier later, that same planet gear will again be in mesh near the transducer so that a similar window of data can be captured. From the number of teeth on the gears, it can be determined which teeth on the planet gear are now in mesh with the annulus gear, and the window of data can be placed in the accumulator in the correct position relative to the first window which was captured [6], as shown in Figure 2. This process of capturing a window of data for each revolution of the planet carrier and placing that window in its correct position in the accumulator is then repeated, as shown in Figure 2. It can be shown that after Np revolutions of the carrier, one window of data has been captured for every tooth on the planet gear. If these windows are chosen to be exactly one tooth in width, then the windows placed in the accumulator form a continuous window of unit amplitude [6]. After

NrNp carrier revolutions, a total of Nr windows will have been captured for each tooth on the planet gear. By dividing the contents of the accumulator by Nr, the signal average of the vibration of the planet gear is calculated over an effective number of Nr ensembles.

It can be shown that the smallest viable window is a single tooth wide, but that broader windows spanning Nv teeth, where Nv is an integer, can also be used. Such windows, when placed in the accumulator, will overlap each other, so that dividing the accumulator contents by NrNv produces the signal average over an effective NrNv ensembles. This has the advantage that more samples of data are being used for the same number of carrier revolutions, thus making more effective use of the data. However, care must be taken that the window width is narrow enough so that the transfer function between the region of tooth contact and the transducer remains constant within that window.

To perform this calculation, it must be known when a planet gear passes the transducer. Under laboratory conditions, a photoelectric transducer could be fitted to the carrier or to the output shaft of the gearbox to sense the carrier position, but this is inconvenient and best avoided in practical applications. Time domain analysis of the signal average of the annulus gear provides a more elegant alternative [6]. The peaks due to the passing of the planet gears have already been noted in the signal average of the annulus gear. By calculating the signal average of the annulus gear and locating these peaks, it is possible to relate the carrier position to the synchronizing signal, enabling the signal average of each of the planet gears to be calculated in turn.

The same technique may be used to calculate the signal average for the sun gear. When a planet gear is closest to the transducer then the transmission path between the mesh of the teeth of that planet gear with the annulus is shortest. Similarly, the transmission path between the mesh of that planet gear with the sun gear, through the planet gear, is also shortest. By synchronizing with the rotation of the sun gear relative to the planet carrier instead of the planet gear with respect to the carrier, the signal average of the vibration of the sun gear can be produced. For a planet gear, only one window can be captured per revolution of the planet carrier, whereas for the sun gear, a window can be captured each time one of the planet gears moves past the transducer. Note that it need not be the same planet gear, so that a window can be captured for every planet, thus accumulating the signal average of the vibration of the sun gear far more quickly. Care must be taken to account fully for the relative motion of the planets about the sun when placing the windows in their correct position in the accumulator.

3. EXPERIMENTAL VERIFICATION

3.1 Epicyclic Gearbox Test Facility

An epicyclic gearbox test facility was constructed featuring a small industrial gearbox, a Brevini model EM1010-MN, having three planet gears with 32 teeth on each of the planet gears, 28 teeth on the sun gear and 95 teeth on the annulus gear. The gearbox was driven by a 40kW three-phase electric motor and was loaded by a conventional dynamometer as shown in Figure 3.

The vibration of the gearbox was measured by a single piezo-electric accelerometer mounted radially on a small steel block bonded to the annulus gear. A synchronizing signal was taken from a photoelectric transducer on the input shaft to the gearbox at a nominal rotational frequency of 19 Hz. The vibration and synchronizing signals were recorded on a Bruel and Kjaer 7003 four-channel FM instrumentation recorder. During replay, the signals were passed through a Wavetek Rockland 752A dual-channel brickwall low-pass anti-aliasing filter.

All software development and data analysis were performed on a DEC LSI11/73 computer with four megabytes of memory, a hard disc drive of 20 megabytes, a floppy disc drive and a Sinetrac analogue to digital converter, running under the DEC RT-11 operating system. The maximum continuous throughput of the analogue to digital converter for extended periods was 4096 samples per second for each of the two channels. To ensure that no aliasing errors occurred, the cutoff frequency of the low pass filter was set to 1600 Hz, approximately 0.8 times the Nyquist frequency.

3.2 Computer Programs

A suite of computer programs was written in DEC RT-11 Fortran 77 to acquire and process the data. The first program, CAPDAT, was designed to sample the vibration and synchronizing signals from the tape recordings at a constant sampling rate and to write the scaled data to a disc file. The second program, DERAVG, calculated the signal average from the data on the disc for the annulus gear by synchronizing with the carrier rotation frequency using a cubic interpolation technique [7].

The third program, DEPOFF, calculated the amplitude of the tooth meshing vibration present in the signal average of the annulus gear by demodulation [3]. The variations in the amplitude of the meshing vibration enabled the position at which the planet gears were nearest to the accelerometer, called the planet offset, to be determined. The fourth program, DEPAVG, implemented the window technique described in this paper by acquiring, mapping and averaging windows of vibration data for the planet gear from the disc at the relative rotation frequency fc using a cubic interpolation technique [7], beginning at the specified planet offset. The fifth program, DESAVG, implemented the technique for the calculation of the signal average of the sun gear. The sixth program, CALENH, was written to implement the narrowband enhancement technique [2] so that small changes in the signal averages could be identified.

3.3 Test 1 Undamaged Gearbox

This test was performed with the gearbox in the original undamaged condition. With a single accelerometer mounted in the radial direction, the gearbox was operated with a load of 12 kW and the vibration was recorded. Program CAPDAT was used to capture data from the tape recording and program DERAVG calculated the signal average for the annulus gear for 100 revolutions of the planet carrier, as shown in Figure 4(a). Program DEPOFF was used to examine the modulation of the tooth meshing frequency produced by the

passing of the planet gears. The result obtained with a centre frequency of 95 orders and a bandwidth of +-15 orders is shown in Figure 4(b). Note the variations which occur in the amplitude of the vibration as the different planet gears move past. The planet offset for the largest peak is 289.5 degrees of carrier rotation.

Program DEPAVG was then used to calculate the signal averages for each of the three planet gears with 32 windows each of width one tooth, each containing 32 samples to give a total of 1024 samples in the signal average. The number of averages calculated was 32, requiring a total of 1024 windows. A slightly different meshing vibration pattern was observed for each planet gear.

3.4 Test 2 Damaged Planet Tooth Meshing with Annulus Gear

The gearbox was dismantled and approximately 0.05 mm was ground from the face of one of the teeth on one of the planet gears to form a narrow flat surface at the pitch line. The gearbox was reassembled so that when under load the damaged tooth face meshed with the annulus gear. With an accelerometer mounted in the radial direction, the gearbox was operated with a load of 12 kW and the vibration was recorded. Signal averages were calculated for the three planet gears as for test 1. Although it was not possible to determine which of the planet gears in Test 2 corresponds to which of the gears in Test 1, a very minor perturbation can be seen in the planet gear signal average shown in Figure 5(a).

After using program CALENH to enhanced the signal average shown in Figure 5(a), the result in Figure 5(b) was obtained, using a bandwidth of +-15 orders about the dominant meshing frequency of 32 orders. There is clear evidence of damage to the planet gear as shown, while no indication of damage was found on the other planet gears. The values of kurtosis for the enhanced signal averages were 10.3 for the damaged planet gear and 2.2 and 2.5 for the undamaged planet gears.

3.5 Test 3 Damaged Planet Tooth Meshing with Sun Gear

The gearbox was again dismantled and the damaged planet gear was turned over so that when under load the damaged face meshed with the sun gear instead of the annulus gear. The gearbox was reassembled and operated with a load of 12 kW with an accelerometer mounted in the radial direction. Signal averages were calculated for the three planet gears as for test 1.

After using program CALENH to calculate the enhanced signal averages with a bandwidth of +-23 orders about the second harmonic of the tooth meshing frequency, the values of kurtosis for the enhanced signal averages were 10.8, 21.6 and 5.6. The high values of kurtosis prove the ability of the signal averaging technique, although it is not possible to determine which of the planet gears has been damaged. Note that it was not possible to determine which of the planet gears in Test 3 corresponds to which of the gears in Tests 1 and 2.

3.6 Test 4 Undamaged Gearbox

The gearbox was dismantled and the planet carrier with the damaged planet gear replaced. The gearbox was reassembled and tested with a load of 12

kW with an accelerometer mounted in the radial direction. The signal average was calculated for the sun gear and variations in appearance across the signal average were observed. Three distinct mesh patterns were seen, varying in amplitude and harmonic content due to the meshing of the sun gear with the three planet gears. The signal average is periodic with the rotation of the sun gear relative to the planet carrier so that any eccentricity or misalignment of the sun gear relative to the planet carrier will cause modulation at once per cycle in the time domain average. These variations are not due to the capture of the vibration data from windows at all three planet gears, as similar signal averages can be obtained using windows from only a single planet gear.

Applying the program CALENH to enhance the signal average about the third harmonic of the tooth meshing frequency at 84 orders with a bandwidth of +-16 orders, gave a kurtosis of 2.3.

3.7 Test 5 Damage to Sun Gear Tooth

The gearbox was dismantled and approximately 0.05mm was ground from the loaded face of one of the teeth on the sun gear to form a narrow flat surface at the pitch line. The gearbox was reassembled and the procedure was repeated as for Test 4, producing the signal average shown in Figure 6(a). Variations can be seen in the signal average as the three planet gears mesh with the sun gear. There is evidence of damage to the sun gear, visible in the signal average, at one location only.

Applying the program CALENH as for Test 4 produces the result in Figure 6(b) with a kurtosis of 5.7. There is clear evidence of damage with a single peak in the trace corresponding to the damaged sun gear tooth meshing with the planet gear opposite the transducer mounted on the annulus gear.

4. DISCUSSION

Test 2 has demonstrated that damage to a single tooth on a planet gear on the face which meshes with the annulus gear will appear in the signal average of only one of the planet gears. This provides confirmation that the technique does in fact allow the separation of the vibration of the individual planet gears as expected.

In contrast, Test 3 has shown that damage to a single tooth on a planet gear on the face which meshes with the sun gear, will appear in the signal averages of all of the planet gears. The reason for this has not been investigated, but it may be that the low inertia of the sun gear compared with the planet carrier, combined with the radial float inherent in the gearbox, enables sufficient radial displacement of the sun gear to occur for the load to be transferred from the damaged planet gear to the other planets. Whatever the reason, the high values of kurtosis prove that the ability to detect damage within the gearbox has not been compromised, even though it is not certain which of the planet gears is damaged.

Test 5 has shown that damage to a single tooth on the sun gear can be identified in the signal average of the sun gear.

5. CONCLUSIONS

A technique has been developed which enables the calculation of the signal averages of the vibration of the individual planet gears in an epicyclic gearbox by viewing the vibration through a small window in time as each of the planet gears passes a vibration transducer mounted on the annulus gear. Laboratory tests on an epicyclic gearbox with deliberate damage to one tooth on a planet gear and to a tooth on the sun gear have shown that such damage can be detected in the signal averages of the individual planet gears and the sun gear using established enhancement techniques.

6. ACKNOWLEDGEMENTS

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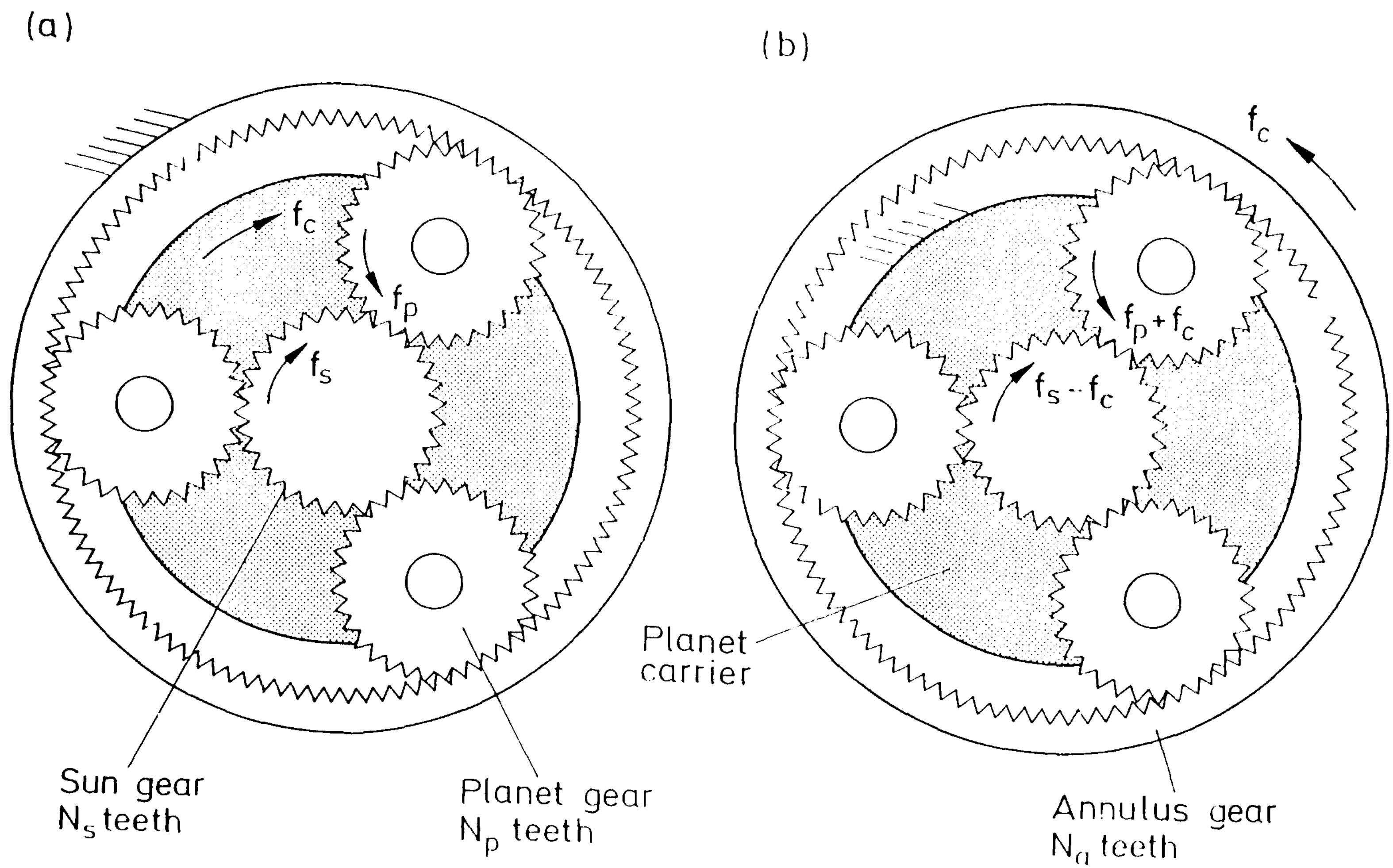

Figure 1. *Simple epicyclic gear system*

(a) Actual motion (b) Relative motion

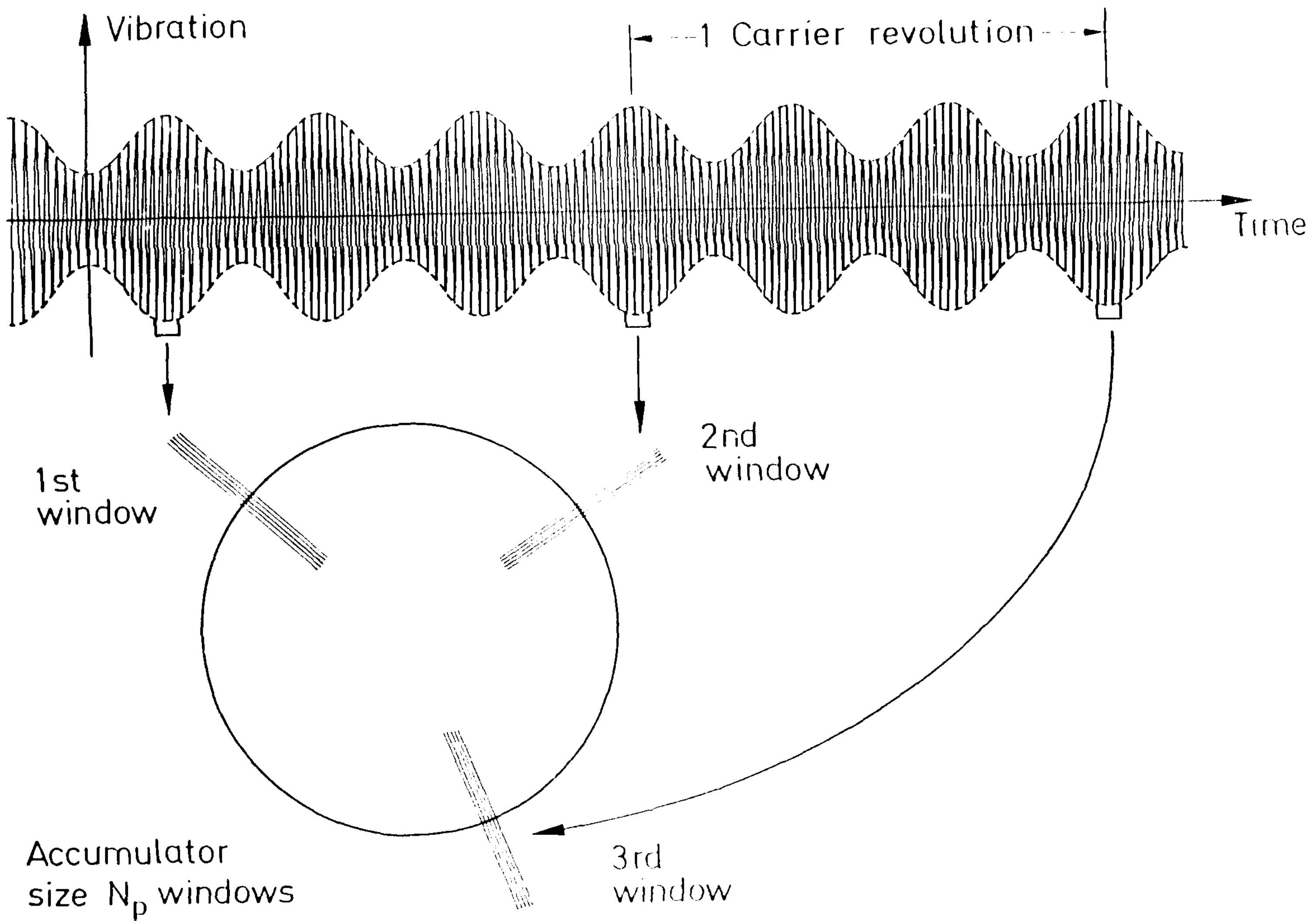

Figure 2 Placing data windows in accumulator

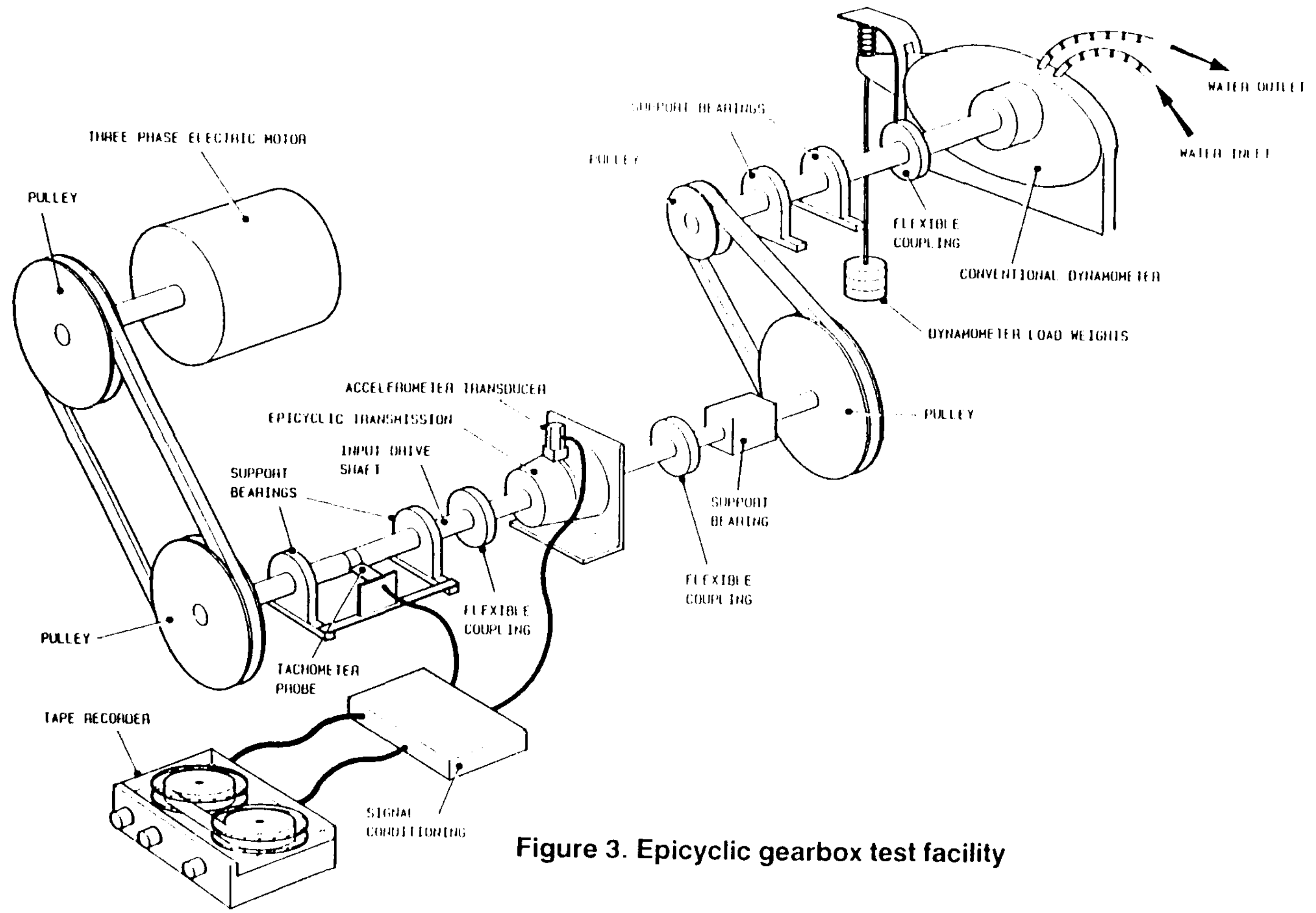

Figure 3. Epicyclic gearbox test facility

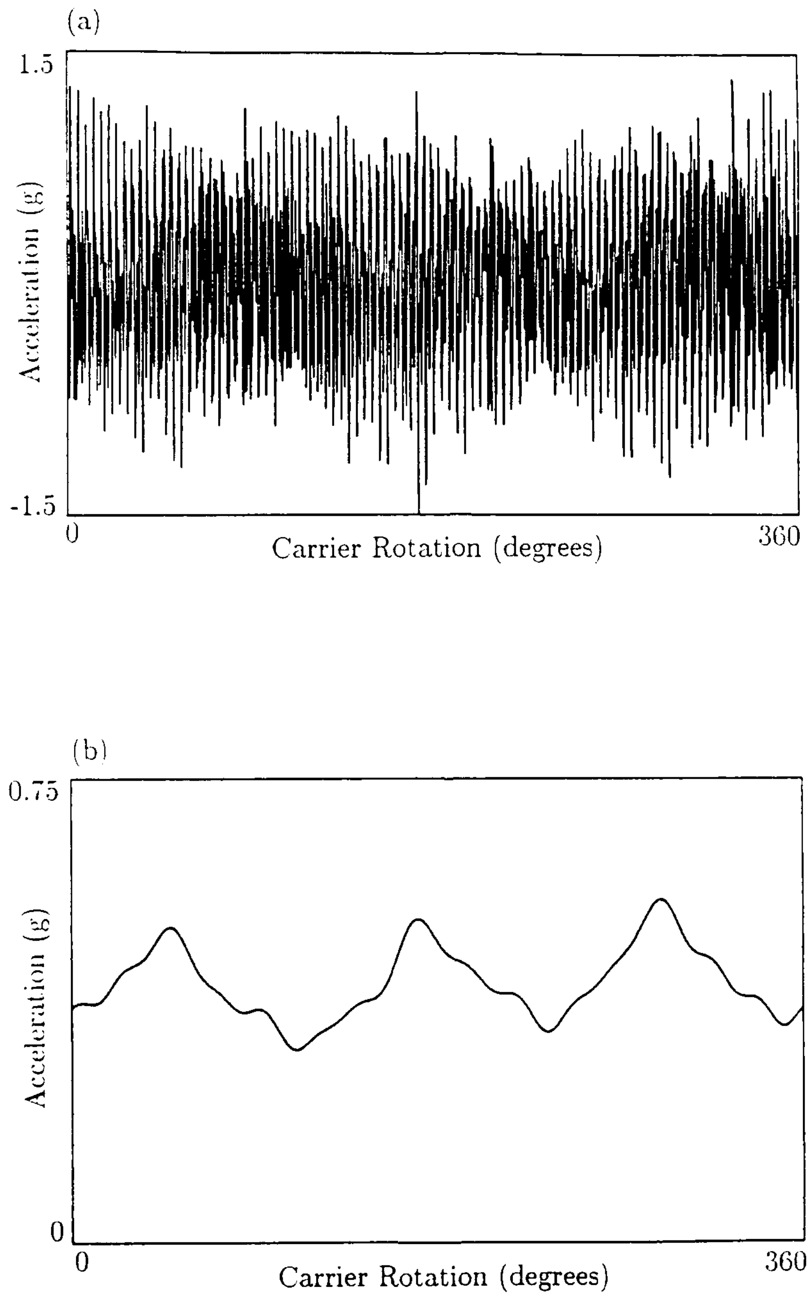

Figure 4. Test 1 Annulus gear
(a) Signal average (b) Enhanced signal average

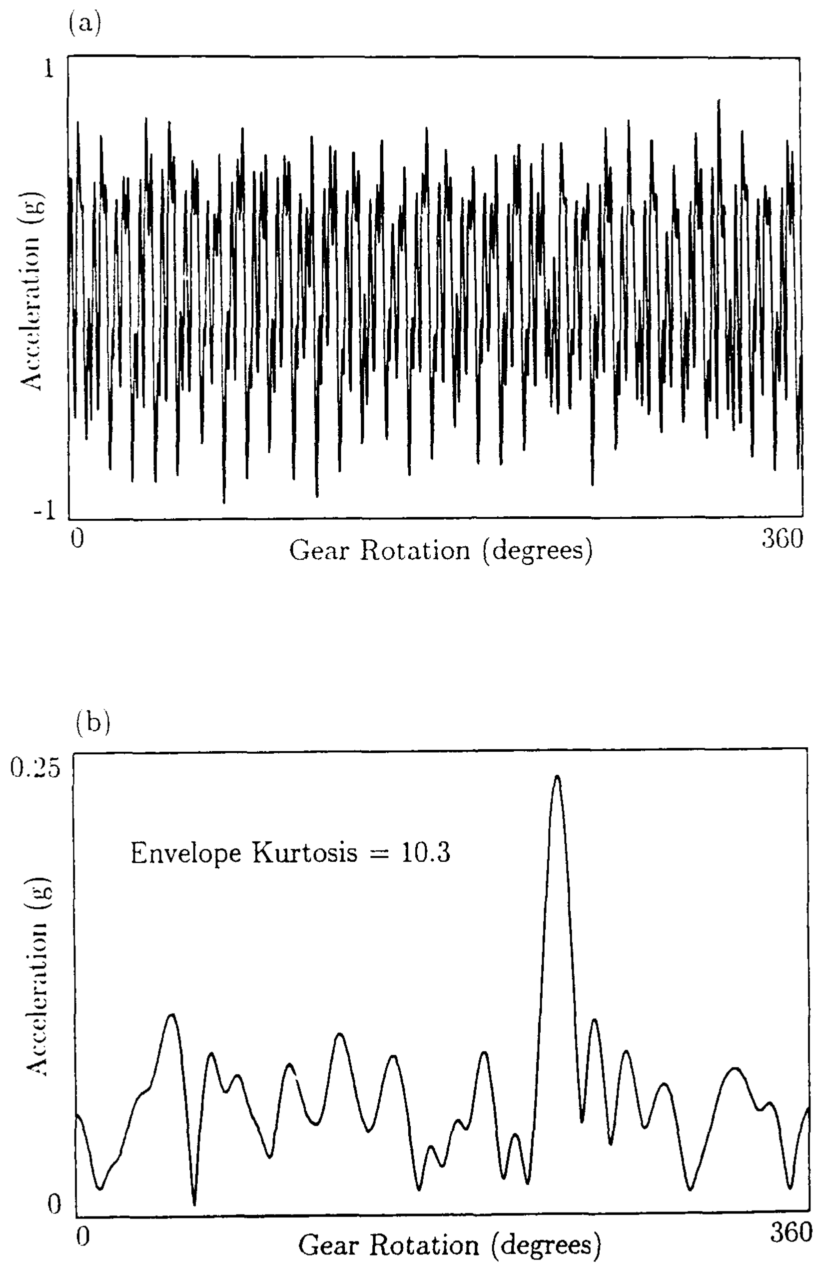

Figure 5. Test 2 Damaged planet gear
(a) Signal average (b) Enhanced signal average

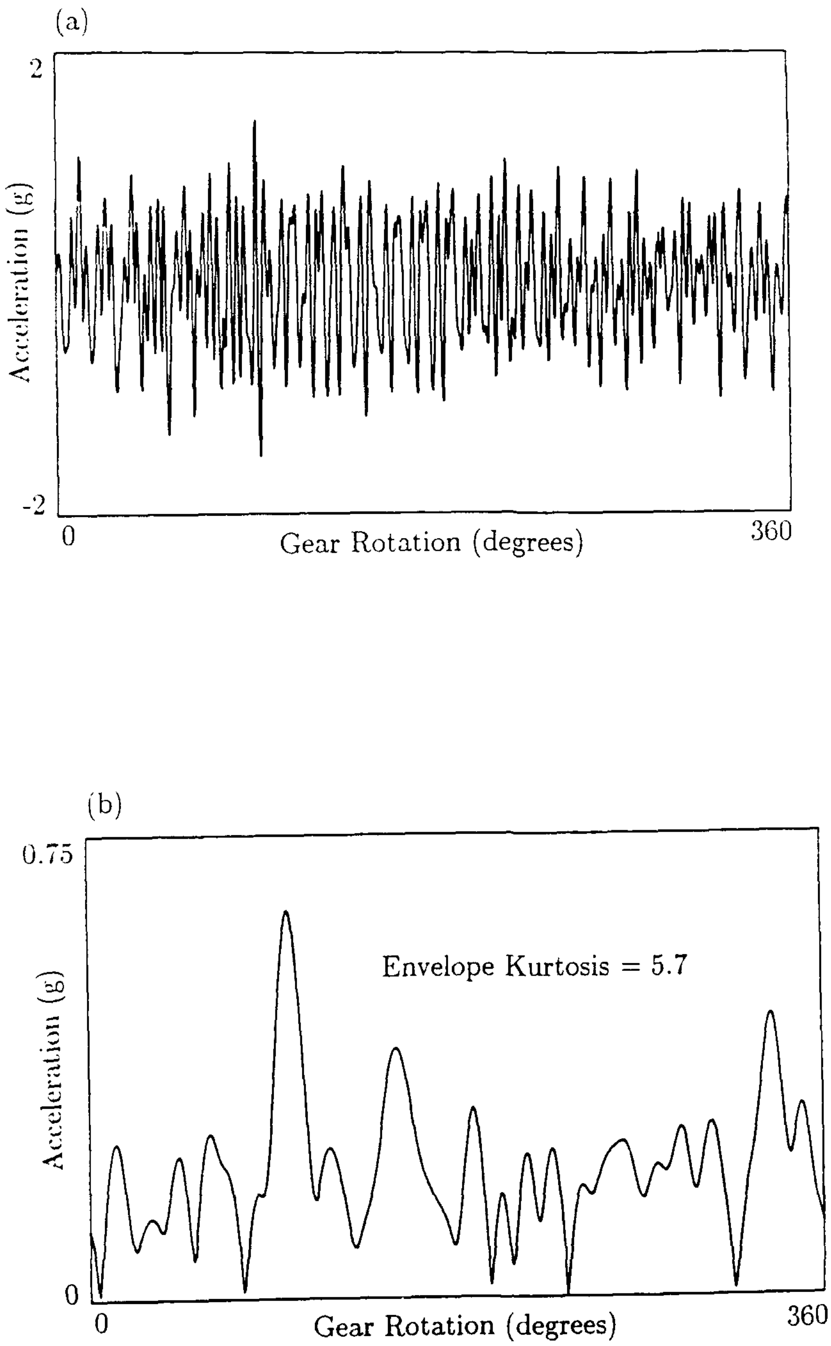

Figure 6. Test 5 Damaged sun gear
(a) Signal average (b) Enhanced signal average

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